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DRIVING EXPERIENCE AND PERCEPTION OF THE LEAD CAR'S BRAKING WHEN LOOKING AT IN-CAR TARGETS

HEIKKI SUMMALA*, DAVE LAMBLE and MATTI LAAKSO

Department of Psychology, Traffic Research Unit, P.O. Box 13, 00014 University of Helsinki, Helsinki, Finland

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Abstract—Perception of the lead car's braking was measured on-road when subjects of various levels of driving experience were looking at a digital display located at the lower part of the windscreen, at the speedometer level, or in the mid-console. The brake lights of the lead car were either working normally or switched off. The results indicated that the detection of the lead car's brake lights, in daylight, is substantially impaired when a following driver is looking at the speedometer area and brake lights do not contribute to detection at all when he/she is looking at a target in the mid-console. Driving experience did not influence performance in detecting a closing headway in peripheral vision, in contrast to improvement in lane-keeping found in an earlier study. It is suggested that such differential ability in using peripheral vision for lane and distance-keeping may mislead experienced drivers when they follow another vehicle and perform certain in-car tasks. © 1998 Elsevier Science Ltd. All rights reserved

Keywords—Brake reaction time, Car following, Dual-task performance, Novice driver, Perceptual learning, Peripheral vision, Time-to-contact

INTRODUCTION

Car driving is a real-life multitask activity which is practised extensively, typically for hundreds of hours per year. This practice appears to result in a learning curve in terms of injury accidents, which levels off in the driver population after 5–7 years and some 50,000 km of driving (e.g. Evans, 1987; Massie et al., 1995; Saarinen, 1984; Summala, 1996a). Increasing evidence indicates perceptual learning concomitant with this change. With practice drivers learn where to search for relevant information and respond to it more quickly (Quimby and Watts, 1981; Summala, 1987; Theeuwes and Hagenzieker, 1993). Early research on driver eye-movement patterns also suggests that experienced drivers look at the road farther ahead than novices and keep their car in the lane with peripheral vision (Mortimer, 1967; Mourant and Rockwell, 1972).

It was shown recently that driving experience is indeed related to lane-keeping when drivers have to perform a foveal in-car task continuously and rely on peripheral vision only in keeping the car within lane boundaries. A marked change appears in ability to do this successfully between the first 1500 and 50,000 km of driving (Summala et al., 1996). This is presumably connected with learning to use more effective visual cues such as lateral speed, and kinesthetic and proprioceptive cues [see, however, Summala (in press)] but the actual perceptual mechanisms are still unknown (Riemersma, 1987; Smiley et al., 1980; Summala et al., 1996).

Such learning helps drivers to perform essential in-car tasks, to look at the speedometer, adjust radio and heat, or search for street names and other relevant information in the traffic environment while keeping safely in a lane. However, drivers adapt their behavior to changes in their skills, and improved lane-keeping performance may make them attend increasingly to non-traffic targets such as mobile telephones, other in-car accessories and sight seeing while driving (Summala, 1994).

Attending to in-car tasks may continue to be detrimental to detecting the braking of the car ahead for the experienced driver, however. For a foveal in-car task in a given position, the retinal eccentricity of the car ahead (distance away from the central high-acuity vision) considerably exceeds that of the edge lines of the road, visible just above the dashboard, and other cues that a driver may use for lane keeping. Practice in lane-keeping also exceeds practice

*Corresponding author. Tel.: 00 358 9 19123450; Fax: 00 358 9 19123489; e-mail: heikki.summala@helsinki.fi

in detecting the braking of the car ahead, especially considering the use of peripheral vision, as the former is continuous and always functional in driving while the latter only occurs in car following. For such reasons distance-keeping with peripheral vision may not show much improvement with driving experience, as distinct from lane-keeping. Drivers may not even have sufficient resolution in peripheral vision for detecting brake light onset of the car ahead (among other light flashes) while looking at the radio and other accessories on the mid-console.

It is well established that humans as well as lower species use time-to-contact information in detection of and response to an approaching object (Cavallo and Laurent, 1988; Lee, 1976; Lee and Reddish, 1981; Regan and Hamstra, 1993; Schiff, 1965; van der Horst, 1990; Wang and Frost, 1992). Accordingly, it was predicted that detecting a reduction in headway with peripheral vision is directly dependent on its looming rate (and the respective time to collision).

We tested the hypotheses with the same forced peripheral vision driving paradigm used earlier in the lane-keeping experiments (Bhise and Rockwell, 1971; Summala, in press; Summala et al., 1996).

METHOD

Subjects

Twenty-eight undergraduates participated, 20 females and 8 males, aged 20–43 years. Six were beginners who had never driven a car (mean age 26.2 years), thirteen were novice drivers who had driven 1000–10,000 km (mean 4300 km, mean age 23.3 years), and nine were experienced drivers who had driven at least 50,000 km during their lifetime (mean 113,000 km, mean age 25.7 years).

The three groups did not differ either in visual function or in sensitivity (d') and response tendency (β) in a visual attention test. Snellen number tables were used for visual acuity, standard perimetry for visual field, and the LH symbol test (Hyvärinen, 1992) for the contrast sensitivity curve. The visual attention test of the FePsy test package (Alpherts and Aldenkamp, 1990) was used to assess the d' and β of signal detection theory to control for possible differences in sensitivity and response bias (decision criterion) (Wickens, 1984). All subjects' visual abilities met the European standard licensing requirements (minimum static acuity of 0.6 or 20/33, and minimum visual field 120°).

Experimental site

A 2 km section of a new freeway not yet opened for traffic was used, which provided good contrast between lane boundaries and pavement. Two lanes 3.75 m in width were marked on a pavement 12.5 m in width with continuous edge lines and dotted (4 m of line with 8 m spacings) center line. There was a slight curve and slope on the section which was balanced across groups and experimental conditions by performing trials at varying locations, two to four trials being performed during each run.

Apparatus

Two instrumented vehicles were used. The lead vehicle was a compact 1988 Lada Samara, in which the driver's use of controls, vehicle speed, and real time were recorded on a computer at 15 Hz, while a Sony AF CCD Handycam recorded the following vehicle. The following vehicle was a 1994 Mitsubishi Galant equipped with a Mitsubishi Motors' multi-beam laser radar device (prototype model) able to measure inter-vehicle distance at a nominal accuracy of 0.1 m. The driver's use of controls, speed, between-vehicle separation and relative speed along with real time were recorded on a computer at 10 Hz. Three Panasonic WV-CD2 video cameras were used, one to record the road scene in front of the car and two recording at different angles of the subject's face, so that glances away from the display could be adequately detected. The three views and the numerical data were mixed onto the same screen and stored on a videotape. The following vehicle was equipped with additional brake and gas pedals for the experimenter in the front passenger seat.

The data collected in the two vehicles were synchronized with the real time stored in both data sets, calibrated by the brake-light onset of the lead car visible on the videotape of the following vehicle.

A single digit LED display (7×13 mm, horizontally centered in a gray box 100×50 mm, 8 mm from the upper edge) controlled by the computer, was used for the in-car task to be looked at continuously by subjects. The first position was just above the dashboard, 15 cm down and 7 cm to the right of the average eye position, at an eccentricity of ca 16° from the sight axis between the eyes and the point of expansion on the horizon. The second was at the level of the speedometer, 31 cm straight down from the average eye position, at an eccentricity of ca 27°. The third was on the mid-console of the car, where the radio and other accessories are normally installed, 51 cm down and 33 cm to the right of the average eye position and at an eccentricity of ca 50° (Fig. 1).

Procedure

The subjects followed the lead car while only fixating on a digital display at three different locations

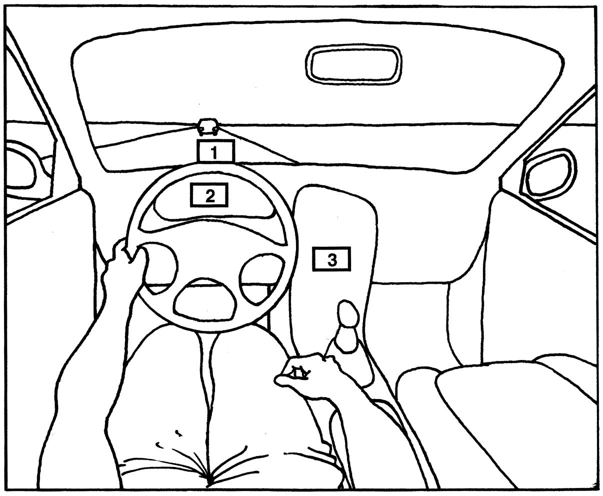

Fig. 1. The subject's view and three in-car display positions.

on the dashboard. They had to brake in response to the lead car's braking, which occurred at an average deceleration of 2.1 msecond^{-2}, with the brake lights either working normally or switched off. The foveal task required naming all the fours and sevens that appeared in a random series of digits (1–9) presented at a frequency of 3 Hz, and thus the task forced three different retinal eccentricities of the car ahead. Four different initial distance and speed combinations were used to vary the time headway and initial retinal size of the car ahead: 15 m headway, with both vehicles initially traveling at 30 km hour^{-1} (1.8 seconds time headway); 30 m and 30 km hour^{-1} (3.6 seconds); 30 m and 60 km hour^{-1} (1.8 seconds); and 60 m and 60 km hour^{-1} (3.6 seconds). Four distance/speed conditions, four foveal tasks (three display positions and the control condition in which subjects watched the rear of the lead car), two brake light conditions (normal and switched off), and two replications (plus two additional replications for the control condition) amounted to 80 trials for each subject, balanced across subjects, and to >2,000 brakings altogether.

All subjects drove the Mitsubishi for 15 minutes prior to testing to allow them to become familiar with the vehicle. For the beginners who had never driven a car, the experimenter (an experienced driving instructor) demonstrated the use of the controls and how to start, accelerate, brake, keep in a lane and turn around at both ends of the closed section of the motorway. During the test trials, the subject first accelerated the car to the initial speed. The experimenter then took over the control of speed and distance, and the subject moved his/her foot onto the brake pedal, turned his/her gaze onto the display and began performing the secondary task. (The distance and lane-keeping were expected to be too demanding for the beginner and novice subjects particularly, and the experimenter also assisted in steering if the heading was about to differ too much from the lead car.) When the headway and speed had stabilized, the experimenter informed the other experimenter in the lead car, with a beacon on the roof of the Mitsubishi not visible to the subject, who started braking after a randomly varied delay.

RESULTS

The brake reaction data were analyzed using a $3 \times 2 \times 4 \times 4$ repeated measures ANOVA, with driving experience (three levels) as a between-subjects factor and brake lights (two levels), speed/distance combination (four levels) and foveal task position (four levels) as within-subjects factors.

Figure 2 shows reaction times as a function of the lead-car eccentricity (forced by different in-car display positions) for each experience group and distance–speed combination. The reaction times to brake onset increased markedly with the increased

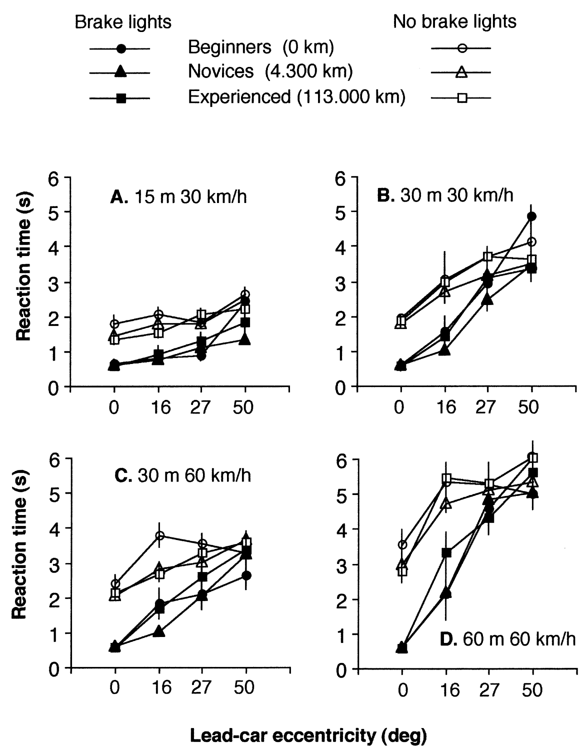

Fig. 2. The average reaction times (and *SE*s) to the braking of the lead car for three driver groups differing in lifetime mileage. The zero eccentricity refers to the control condition in which the driver fixes his/her eyes on the car ahead, whereas the higher eccentricities (the visual angle between the display and car ahead) imply continuous looking at an in-car digital display requiring sampling of all 4s and 7s from a random series of digits. The speed and between-vehicle distance was varied (A–D), and brake lights either worked normally (●, ▲, ■) or were disconnected (○, △, □) The average deceleration was 2.1 msecond^{-2}.

eccentricity of the lead car (for ANOVA results see Table 1), and were accentuated with increasing distance. The influence of brake lights substantially decreased when the foveal task was at speedometer level, and it did not affect reactions at all when the foveal task was in the mid-console (the interaction between the brake light condition and eccentricity was highly significant). Three post hoc ANOVAs were conducted each using two levels of speed/distance, to examine the effect of speed and distance on reaction times. The analysis revealed that vehicle separation was a significant factor effecting brake reactions (30 km hour^{-1} and 15 m versus 30 m, $F_{1,25}=158.19$, $p<0.001$; and 60 km hour^{-1} and 30 m versus 60 m, $F_{1,25}=111.40$, $p<0.001$), whereas speed was not (30 m and 30 km hour^{-1} versus 60 km hour^{-1}, $F_{1,25}=3.73$, $p=0.065$).

Beginners did not perform worse when looking at the in-car target: neither the main effect of driving experience nor any related interaction was significant over the whole data (Table 1). The groups did not differ in the secondary task performance either, proportion of missed items for each group being: beginners 10.8%, novices 9.6%, experienced 11.6%.

As compared to the control condition, the average delay in terms of brake reaction time, across the four speed/distance conditions and all subjects, was 0.9 seconds for the lower windscreen position, 2.1 seconds for the speedometer and 2.9 seconds for the mid-console position.

Figure 3 shows angular velocity as divided by the corresponding visual angle of the lead car at the moment of brake reaction, at various lead-car retinal eccentricities. This is equivalent to the inverse of time-to-collision, as estimated from the distance and speed difference as proposed by Hoffmann (1968) and Hoffmann and Mortimer (1994). The data are collapsed over the experience groups, and only includes the condition with the brake lights disconnected. The deterioration in visual performance with increasing eccentricity of the target may be only dependent on the decrement of the visual acuity in the peripheral vision. Therefore, the retinal eccentricity is also rescaled according to visual acuity such that the x-axis additionally shows the cortical magnification required for similar resolution (Virsu and Hari, 1996; Virsu et al., 1987), that is, the coefficient which shows how much the lead car's figure in the peripheral retina should be enlarged to give a resolution comparable to that provided when looking directly to the lead car.

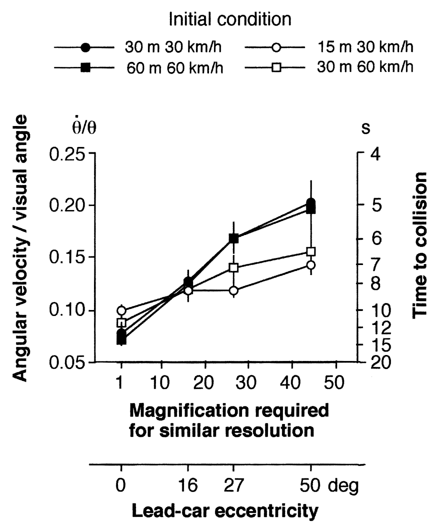

Fig. 3. Angular velocity as divided by the corresponding visual angle of the lead car (equals to the inverse to time-to-collision) at the moment of brake reaction, at various lead-car retinal eccentricities. The (cortical) magnification factor (Virsu and Hari, 1996), also shown on the x-axis, indicates how much the lead car's figure in the peripheral retina should be enlarged to give a resolution comparable to that provided when looking directly to the lead car. The data are collapsed over the experience groups, with brake lights disconnected.

Table 1. Results of repeated measures ANOVA for the brake reaction time data

Factor	*df*	*F*	*p*
Eccentricity	3.75	178.52	<0.001
Speed/distance	3.75	152.37	<0.001
Brake lights	1.25	141.72	<0.001
Eccentricity × speed/distance	9.225	18.89	<0.001
Eccentricity × brake lights	3.75	29.88	<0.001
Speed/distance × brake lights	3.75	7.22	<0.001
Eccentricity × speed/distance × brake lights	9.225	5.56	<0.001
Driving experience	2.25	0.92	0.413
Driving experience × brake lights	2.25	0.28	0.756
Driving experience × speed/distance	6.75	0.0	0.875
Driving experience × eccentricity	6.75	0.78	0.585
Driving experience × brake lights × speed/distance	6.75	0.85	0.535
Driving experience × brake lights × eccentricity	6.75	1.56	0.170
Driving experience × speed/distance × eccentricity	18.225	1.59	0.064
Driving experience × brake lights × speed/distance × eccentricity	18.225	0.52	0.947

DISCUSSION

The results support the present hypothesis that detecting closing-headway situations with peripheral vision does not improve with driving experience as lane-keeping does (Summala et al., 1996), at least within the range of 0 to ca 100,000 km of lifetime mileage. It is presumed that no further improvement in peripheral detection will occur after this amount of mileage, which represents 1000–2000 hours of practice in normal driving, among ordinary private drivers at least. However, perceptual learning may occur in detecting deceleration of the car ahead in the foveal and parafoveal region, much practised in normal driving, resulting in lowered perception thresholds. Preliminary corroboration is provided by the results in the control condition. Also, when passengers in an approaching car estimate time-to-collision with a stationary object, limiting the field-of-view to 10° does not cause experienced drivers' performance to deteriorate. In contrast, beginners benefit from full field-of-view (Cavallo and Laurent, 1988). This suggests that perceptual learning occurs, caused by the lead car's looming retinal image only.

Although it was not possible to directly address the cues the subjects used, some comments implied that they did not use the gradient between the car in front and their own, such as texture of the pavement and surroundings and dotted center line (Gibson, 1979; Lee and Lishman, 1977; Cavallo et al., 1997); the subjects rather reported that the lead car suddenly emerged in the peripheral vision. Thus, it is assumed that the looming retinal image of the car ahead is the major cue for detection of its deceleration (relative speed). The absolute perceptual threshold for detection of the relative speed in the fovea, in terms of angular speed of the approaching object, is ca 0.002–0.003 rad second^{-1} (Hoffmann and Mortimer, 1996) which corresponds to the foveal thresholds found in these data at the 60 m initial distance (0.002 rad second^{-1}). To allow fast dynamic control of the environment, the visual system presumably relates the angular speed of the approaching object (θ') to its retinal size (visual angle, θ), equalling the inverse of time-to-collision (Hoffmann, 1968; Lee, 1976). It is presumed that this model works in peripheral vision as well and predicts that with increasing eccentricity of the car ahead the detection threshold (θ'/θ) should grow proportionally as the resolution of the retina (and the corresponding cortical magnification) decreases. The present results (Fig. 3) support this model up to a point, suggesting an approximately linear function between the detection threshold and the degree of the visual eccentricity (angle and cortical magnification) of the car ahead. The flatter function for the 15 m/30 km hour^{-1} and 30 m/60 km hour^{-1} conditions may be due to more difficult experimental circumstances at these shorter time distances (1.8 seconds versus 3.6 seconds headway for the other conditions). For safety reasons, the lead car could not be brought to a complete stop and, at the shorter time distance conditions, brake force of the lead car was somewhat reduced sometimes to avoid too high risks. This resulted in a lower relative speed at the end of the braking and less angular speed at the moment of reaction.

In conclusion, it is suggested that the detection of deceleration of the car ahead when looking away from it is only dependent on the properties of the visual system. Although the use of peripheral vision can be practised (Johnson and Leibowitz, 1975), normal driving does not provide relevant practice for learning this task.

The fact that one in-car task causes two driving subtasks to deteriorate differently, considering visual performance capabilities, is inclined to mislead a driver with accumulating experience. It should be noted that improved lane-keeping capability is presumably one of the mechanisms which contribute to the subjective feeling of control, often thought to contribute to accident involvement through high speed and short safety margins (Gregersen, 1996; Gregersen and Bjurulf, 1996; Jonah, 1986; Katila et al., 1996; Lajunen and Summala, 1995; Näätänen and Summala, 1976; Summala, 1988).

The present results show a substantial delay in brake reaction times when a driver is looking away from the lead car which brakes, whether he/she is a novice or more experienced as a driver. In daylight, brake lights help little or not at all in detecting the lead car's deceleration, if the following driver is looking at his speedometer or another target inside the car farther away from the lead car.

Inferior performance in distance keeping during in-car tasks and differential perceptual learning in lane and distance control call for further measures to reduce rear-end crash risks. This is even more important as the car industry is providing new and more complicated information technology to compete for the drivers' attention. Among many means to reduce exposure to rear-end crashes (Summala, 1996b, p. 113), advanced distance control systems appear promising. However, the reliability of the control (and warning) systems is a key question as such support systems may lure drivers to allocate ever more time to in-car tasks. Therefore, standards for the location and interface of in-car equipments are needed, and efforts to monitor driver fatigue unobtrusively, in terms of eye closures, should also cover driver attention monitoring more broadly, to warn a driver if he/she looks away from the road too long.

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